Brain Correlates of Mathematical Anxiety

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Abstract

Mathematical anxiety is defined as apprehension and stress surrounding situations involving mathematical information and reasoning. This study utilized an electroencephalogram (EEG) paradigm to observe the effect that anticipation before mathematical performance and feedback after mathematical performance may have on an EEG-based anxiety response. The EEG paradigm consisted of a series of algebraic equations, arithmetic equations, and lexical questions, where participants decided if the equation/sentence was mathematically/grammatically correct or incorrect. Results, collected from a sample of N = 7 Research Experience Program (REP) students at The Ohio State University (OSU), suggested that cueing before math performance and feedback after math performance led to changes in cortical function, particularly within the algebra and arithmetic tasks. There was little evidence to suggest that cue and feedback influenced cortical functioning during the lexical task. With more comprehensive knowledge behind mathematical anxiety, future researchers can investigate its developmental origins, and perhaps, ultimately develop a manageable educational intervention to better general mathematical performance by overcoming this negative emotional response.

Introduction

Anxiety elicited by math is often characterized as feelings of stress that lead to an avoidance of situations involving mathematical reasoning (Ashcraft & Ridley, 2005; Young, Wu, & Menon, 2012). Math anxiety can start as early as first grade and can adversely affect an individual for his/her entire life (Harms, 2012; Maloney & Beilock, 2012). This negative emotional response frequently manifests as reoccurring thoughts of deep concern about one's assumed lack of mathematical knowledge that distracts one from accurately solving a math problem (Harms, 2012). Mathematical anxiety can be highly detrimental to the learning and understanding of mathematics, and has been shown to hinder mathematical problem solving (Ma, 1999; Young et al., 2012).

Because math is necessary and obligatory in our every day lives (i.e., adding up a grocery bill, or financing a new car or house), avoidance or disruption of mathematical reasoning can impede cognitive, academic, and emotional attainment (Maloney & Beilock, 2012). Furthermore, better understanding of mathematical anxiety is imperative because of the potential for math anxiety to become a self-fulfilling prophecy leading to delays in learning throughout the lifespan (Morris, 1981). For instance, one fears math problems, this fear distracts him/her from focusing on correctly solving the math problem, and as a result, he/she not only fails to solve the math problem accurately, but also is further inclined to avoid a mathematical situation in the future (Morris, 1981). The replication of this self-fulfilling prophecy over several years may explain why many individuals with high math anxiety are biased against taking mathematics courses or entering into a career that relies heavily on mathematical reasoning (Lyons & Beilock, 2012a; Maloney & Beilock, 2012).

Affective Consequences. One of math anxiety's more critical consequences is its relationship to brain regions associated with affective outcomes. Previous research on mathematical anxiety has revealed distinct patterns of brain activation in regions associated with negative emotions, such as actually feeling pain (Maloney & Beilock, 2012). Lyons and Beilock's (2012a) research identified that individuals with high math anxiety exhibit an increase in activity in brain regions associated with "pain-related experience and the detection of a potentially threatening bodily event," specifically the dorso-posterior insula (INSp) and mid-cingulate cortex (MCC), while merely thinking about solving a math question (p. 5). Results also illustrated that individuals with high math anxiety display an increase in these pain-related brain regions when anticipating a math question, but not when actually attempting to solve a math question (Lyons & Beilock, 2012a). In summary, math-related anxiety elicits the most pain while individuals are simply presented with the idea of having to solve an upcoming mathematical equation; yet, as soon as people attempt to solve the question, the pain decreases (Lyons & Beilock, 2012a). The findings of Lyons and Beilock (2012a) are significant for understanding the beginning of the negative emotional impact produced by mathematical anxiety.

As researchers delve deeper into the adverse effects of high mathematical anxiety, it could be argued that the brain regions associated with pain may also be related to other affective and cognitive regions. For example, Young et al. (2012) similarly investigated the neural correlates of mathematical anxiety within a sample of children. Children with high math anxiety experienced greater activation in brain regions such as the right amygdala, which is associated with negative emotions and fear response (Young et al., 2012). Additionally, Young et al (2012) reported that while these children with high math anxiety were attempting to solve a mathematical question, they demonstrated less activation in brain regions associated with math reasoning, such as the posterior parietal and dorsolateral prefrontal cortex. In sum, this study found that, after individuals with high math anxiety feel pain, brain regions linked to mathematical reasoning were hypoactive while attempting to solve math questions. Such findings provide yet another important step in fully understanding the neural timeline of mathematical anxiety.

Cognitive Consequences. Research has also investigated the relationship between the neural correlates of mathematical anxiety and its effect on the working memory of individuals with high math anxiety. Working memory is the effortful mental process that allows one to manipulate pieces of important information while also keeping track of or retrieving additional information from one's past memories (Ashcraft, 2002). Research has shown that working memory is a critical component of math problem solving (Ashcraft, 2002; Maloney & Beilock, 2012). Pervious research has hypothesized that as mathematical questions become more difficult, working memory becomes more essential to accurately solve the problem (Ashcraft, 2002; Ashcraft & Kirk, 2001). In other words, an algebra equation would require more utilization of working memory than would a routine arithmetic equation, as the former requires one to keep track of a sequence of operations, whereas the latter involves only adding or subtracting given quantities (Ashcraft, 2002; Ashcraft & Kirk, 2001).

Consequently, this research has suggested that working memory may become disjointed and confused in the presence of mathematical anxiety. Concentrating fully on the more complicated primary task (i.e., solving a mathematical problem) at hand becomes much more difficult when one's working memory is distracted by thoughts of self-doubt about one's mathematical abilities (Ashcraft, 2002; Eysenck & Calvo, 1992). Individuals with high mathematical anxiety are adversely affected by their own worries as they become preoccupied with their fears of inadequate math knowledge (Ashcraft, 2002). Math anxiety becomes the primary focus, which in turn, prevents working memory from adequately aiding in solving the math question (Ashcraft, 2002).

Given the erosion of confidence, increase in anxiety, and decrease in working memory capacity, it is critical that future mathematical anxiety research consider both the affective and cognitive consequences of this negative emotional response (Maloney & Beilock, 2012). In order for researchers to truly understand how individuals learn and process numerical and mathematical reasoning skills, studies must not overlook these physiological outcomes associated with math anxiety (Maloney & Beilock, 2012).

Relationships with Other Forms of Anxiety. That said, it is not yet clear whether mathematical anxiety is distinct from or related to other forms of anxiety. As a result, examining the distinction between this type of anxiety response and general anxiety or overall test anxiety is another area of needed additional research. Llabre & Suarez (1985) state that further investigation is needed in order to differentiate between math anxiety and general anxiety since the degree to which they differ will have a critical impact on the treatment of both types of anxiety. Other researchers have explored the potential distinction between mathematical anxiety and test anxiety. Kazelskis et al (2000) depicted math anxiety and test anxiety as two separate experiences. These researchers examined the conceptual difference between the two constructs and found that the correlation between the two types of the anxiety was fairly high, but the study concluded that the differences between the two phenomena needed to be investigated further (Kazelskis et al., 2000). However, other researchers have argued that mathematical anxiety and test anxiety are not interchangeable since math anxiety measures are more closely correlated to each other than with test anxiety measures (Hunsley, 1987; Dew, Galassi, & Galassi, 1983; Dew, Galassi, & Galassi, 1984).

Pervious Literature Limitations. Despite the importance of the findings presented above, previous studies have employed a fundamental issue – utilizing only questionnaire-based assessments to measure mathematical anxiety. In particular, the vast majority of studies have used measures related in some way to the Mathematics Anxiety Rating Scale (MARS). Briefly, the MARS is often used to gauge how anxious individuals feel in a variety of mathematical reasoning situations (Richardson & Suinn, 1972). For example, the questionnaire asks individuals to rate on a five point scale how anxious they feel from 'not at all' to 'very much' when, "studying for a math test" or "calculating a restaurant bill" (Ashcraft, 2002, p. 181). This scale has been shown to have "high test-retest and internal consistency reliability" (Richardson & Suinn, 1972, p. 551). Brush (1978) found that undergraduates majoring in physical sciences scored lower on the MARS than undergraduates majoring in social sciences, with undergraduates majoring in humanities scoring the highest. High MARS scores were also inversely related to "number of years of high school mathematics, number of terms of Calculus, and grades achieved in high school mathematics" (Brush, 1978, p. 485). Such findings seem logical given that individuals with higher mathematical anxiety avoid situations, and subsequently college majors, etc., that require a heavy amount of mathematical reasoning (Lyons & Beilock, 2012a; Ashcraft & Ridley, 2005; Young et al., 2012).

Although the MARS questionnaire-based measure has been shown to be reliable and valid when discriminating between individuals with high and low mathematical anxiety, it does not provide any insight into the temporality of mathematical anxiety in real time. In order to better understand the neural timeline of math anxiety, researchers must observe how the brain responds to different math-related stimuli in real-time. Self-report questionnaires do not aid in evaluating the physiological effects of stimuli. Temporal data will help researchers understand not only 'how' the brain of highly math anxious individuals functions when presented with math-related stimuli, but also 'when' individuals have a brain-based anxiety response in real-time. Static self-reports and localized measures do not aid in answering these types of crucial research questions.

Present Study. Electroencephalogram (EEG) provides a useful means to address these issues. EEG temporally records the location and magnitude of electrical brain activity while an individual performs a cognitive task, such as a math problem. Because of its ability to record fast electrical activity, EEG has the advantage of taking very precise time measurements with resolution down to a millisecond or less. This type of data would greatly improvement our current understanding of math anxiety's neural timeline. For example, the anticipation, or cueing, of math problems or feedback given after one solves a math question may differentially affect cortical processing, working memory, and subsequent performance. The possibility that a math anxiety response could be elicited by a cue or by feedback on the accuracy of one's answer, or both, has not been examined. EEG recordings of this difference in cortical activity would aid in understanding how the brain of individuals with high mathematical anxiety actually reacts in real-time to math-related stimuli. For example, beta activity has been associated with anxiety in other domains (Pavlenko, Chernyi, & Goubkina, 2010). Specifically, the desynchronization of beta activity has been related to working memory (Ashcraft & Krause, 2007; Lyons & Beilock, 2012b). More desynchronization of beta activity is associated with optimal working memory processes, while less desynchronization of beta activity is associated with less working memory functioning (Ashcraft & Krause, 2007; Lyons & Beilock, 2012b). This measurement is ideal for studying mathematical anxiety because, as stated before, hard math problem solving (i.e., algebra) inherently utilizes more of one's working memory than easier math problems, such as arithmetic (Ashcraft, 2002). Moreover, previous research has not investigated math anxiety through the means of EEG. This present, original study utilizes the objective physiological measure of EEG to observe the effect of cueing before mathematical performance and feedback following mathematical performance on the cortical math anxiety response.

Consequently, this thesis addressed the following three hypotheses. First, participants will have a stronger EEG-based anxiety response to cued mathematical questions relative to non-cued mathematical questions. In other words, participants will demonstrate a greater difference in the cortical electrical activity as measured by EEG in response to the anticipation of an upcoming math problem (i.e., cueing). Second, participants will have a stronger EEG-based anxiety response to feedback about their ability given after the completion of mathematical questions relative to not receiving performance feedback. Again, participants will demonstrate a greater difference in the cortical electrical activity as measured by EEG in response to feedback about their mathematical performance given after the completion of a question. Lastly, this thesis hypothesized that this difference in the cortical electrical activity is specific to mathematics and not generalized to overall learning. For example, the EEG-based anxiety response is elicited only by mathematical questions and not by lexical problems.

Methods

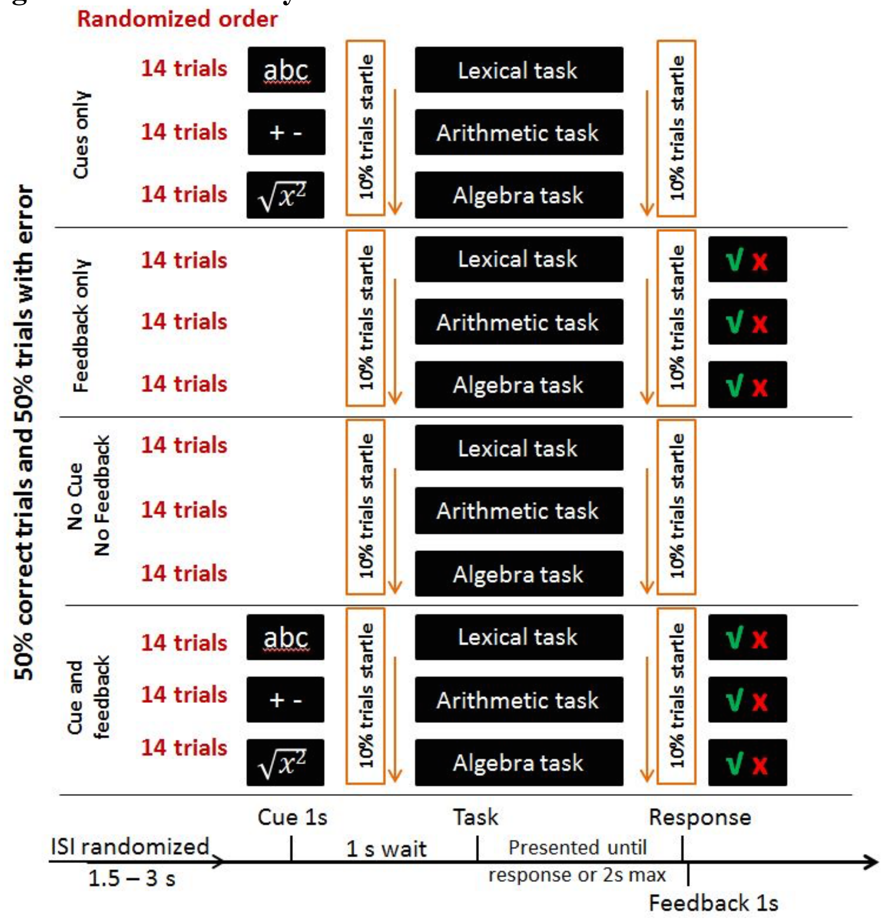
Participants

This thesis examined N = 7 students drawn from the Research Experience Program (REP) at The Ohio State University. REP students received credit from an Introductory Psychology course as a part of their enrollment. All students were right-handed. Two male students and five female students were sampled, with ages ranging from 18 to 26 years old. Five students reported their race as White, while one student reported her race as Asian and another student reported her race as Black or African American. Students had been in school for a total of 12 to 13 years, with four students currently studying within the College of Arts and Sciences, two students currently studying within the College of Medicine, and one student currently studying within the College of Nursing.

Procedure

Upon arrival to the OSU Computational Memory Laboratory and the Petrill Laboratory in Lazenby Hall, REP students were given two copies of the informed consent forms – one copy was signed and dated for laboratory records, and the other was for the student's records. Students then went through the gelling process to secure the non-invasive, 64 electrode-channel, EEG cap on the head. At this time, demographic (i.e., age, gender, race, ethnicity, etc.) and academic (i.e., years of schooling completed, college major, college GPA, etc.) information was collected via an 'About Me' questionnaire (See Appendix A). The EEG paradigm (explained in detail below, and shown in Figure 1) is comprised of a series of algebraic equations, or hard math problems such as 'X (a+b) = Xa+Xb', and a series of arithmetic equations, or easy math problems such as '1+2+3 = 6'. Students were instructed to decide if the equation was correct or incorrect. Students also completed a series of lexical

Figure 1: EEG Anxiety Task



questions, where they were asked to recognize grammatical errors in sentences like 'The dog chase the ball'. The lexical task was incorporated to examine if this anxiety response was specific to math, or if it was generalized to all learning.

Before starting the EEG anxiety task, students first participated in a practice run. Task instructions were read aloud to each student to explain the task (See Appendix A). The practice run took approximately 2 to 5 minutes to complete and consisted of roughly six full trials (i.e., two trials per task type – lexical, arithmetic, and algebra) with both cue and feedback stimuli. The purpose of the practice run was to acquaint the students with the task stimuli and allow for questions about the task before starting. After finishing the EEG task, students completed two self-report questionnaires – the MARS to measure their math anxiety, and the State-Trait Anxiety Inventory to measure their general anxiety (See Appendix A) – that took approximately 10 to 15 minutes to complete. The general anxiety questionnaire was included to investigate if this negative emotional response was also related to overall anxiety. Once the entire testing session was completed, a debriefing point took place.

EEG Paradigm

The EEG paradigm took approximately 40 to 60 minutes to complete and students were tested individually. It was set up in a 3x2x2 within-subjects design – three different problem types (i.e., algebra, arithmetic, and lexical), the presence or absence of a cue (i.e., cue before the task vs. no cue before the task), and the presence or absence of feedback (i.e., feedback after the task vs. no feedback after the task). As shown in Figure 1, these three tasks (i.e., algebra, arithmetic, and lexical) are presented in eight blocks that are divided up in two sessions. Within each session, there are four blocks: the 'cue only' block, the 'feedback only' block, the 'cue and feedback' block, and the 'no cue and no feedback' block (explained in detail below). The order of these four blocks was randomized within each session.

1. In the 'cue only' block, all trials for each task (i.e., algebra, arithmetic, and lexical) were preceded by a visual cue.
2. In the 'feedback only' block, participants receive feedback on their performance after their response to each trial.
3. In the 'cue and feedback' block, participants receive both the cue before each trial and the feedback after each trial.
4. In the 'no cue and no feedback' block, participants receive neither the cue before nor the feedback after.

The cue, which flashes on the screen for 1 second, anticipates which task will follow, and is separated from the task by a 1-second interval. The cue signals are represented by different symbols – for example, 'ABC' represents an upcoming lexical task, '$\sqrt{X^2}$' represents an upcoming algebra task, and finally '+ -' represents an upcoming arithmetic task (see Figure 1). The feedback (represented by either a green check mark for correct, or a red X for incorrect) is presented immediately after each response for 1 second. Each trial is separated by a randomized interval of between 1.5 to 3 seconds. Each block includes 42 trials: 14 lexical, 14 algebraic, and 14 arithmetic trials. The order of these 42 trials is randomized within each block, and each student completes all 42 trials in each block. The purpose of these two blocks is to examine the potential impact of anticipatory/feedback anxiety across the three tasks.

Finally, a startle stimulus, represented by different noises (i.e., a beep), was presented for 20% of trials across all tasks (i.e., algebra, arithmetic, and lexical) and conditions (i.e., 'cue only' block, 'feedback only' block, 'cue and feedback block', and 'no cue and no feedback' block), either before (10%) or after (10%) the task. The purpose of this startle stimulus was to provide general affective reactivity and to evaluate the effects of fatigue and habituation across all the tasks.

In sum, as illustrated in Figure 1, a full trial may start with a randomized cue (i.e., ‘ABC’, ‘$\sqrt{}X^2$’, or ‘+ -’), flashing on the screen for 1 second, that marks which task will follow (i.e., lexical, algebra, or arithmetic). Then a waiting time of 1 second separates the cue from task presentation. The task is presented until the student selects if the equation/sentence is mathematically/grammatically correct or incorrect by pressing one of two keys on the keyboard with different hands, or 2 seconds have elapsed. A startle stimulus may randomly be presented either before or after the task. Following the student’s response, feedback of either correct or incorrect, again represented by either a green check mark for correct, or a red X for incorrect, depending on the accuracy of the student’s response, appears on the screen for 1 second. EEG data were collected continuously and events of interest (i.e., trials) were segmented around each stimulus onset. In this way, it was possible to examine the effects of cue and feedback on the anxiety response for each mathematic and lexical stimulus.

Data Analysis

As explained more fully in Paul, Sederberg, & Feth (2015), EEG data were recorded in an electrically-shielded and sound-attenuated room using a 128-electrode Brain Products actiCAP system (BrainProducts GmbH, Munich, Germany) via a 64-electrode montage connected to a Brain Products actiCHamp amplifier. EEG signals were recorded using a Dell Optiplex 980 desktop computer with a 2.5 GHz Intel Core i5 vPro processor sampling data at 1000 Hz (Paul, Sederberg, & Feth, 2015). EEG data were first re-referenced offline to linked mastoids and high-pass filtered above .25 Hz via the Python Time Series Analysis (PTSA) library (http://ptsa. sourceforge.net) (Paul, Sederberg, & Feth, 2015). Eyeblink and motion artifacts were corrected for using a wavelet-enhanced independent components analysis algorithm without having to reject events due to movement or muscle interference (Paul, Sederberg, & Feth, 2015; Castellanos & Makarov, 2006). Epochs of data were set between -250 to 1000 ms with 0 ms corresponding to event onset, downsampled to 200 Hz (Paul, Sederberg, & Feth, 2015). Then, using frequency bins of delta (2–4 Hz), theta (4–8 Hz), alpha (9–14 Hz), beta (16–26 Hz), low gamma (28–42 Hz), and high gamma (44–100 Hz), spectral power was calculated through Morlet wavelets (five wave cycles) (Paul, Sederberg, & Feth, 2015). For each wavelet a Gaussian window was applied, therefore, in the cases of delta activity where power calculations are less accurate over the 1 s epoch, oscillatory power was estimated at the peak (Paul, Sederberg, & Feth, 2015). Next, EEG data were averaged around each metric condition of binary strong beat (B1, $N = 360$ per subject), binary weak beat (B2, $N = 360$), ternary strong beat (T1, N = 240), first ternary weak beat (T2, $N = 240$), and second ternary weak beat (T3, $N = 240$) (Paul, Sederberg, & Feth, 2015). Total power values for each time point, channel, and frequency were converted to z-transformed log power and downsampled to 50 Hz (Paul, Sederberg, & Feth, 2015). For statistical analysis, final EEG data were either baseline corrected from -100 to 0 ms prior to each event onset (to examine event-related changes in total oscillatory power) or left uncorrected at the baseline to examine global states of oscillatory power (Paul, Sederberg, & Feth, 2015). EEG data uncorrected at the baseline may measure neural activity not strictly time-locked to each stimulus but instead oscillatory activity related to the metric type (i.e., binary vs. ternary) (Paul, Sederberg, & Feth, 2015). Due to this study's low sample size (N = 7), EEG data analysis found only strong trends. The relevant conditions are presented below.

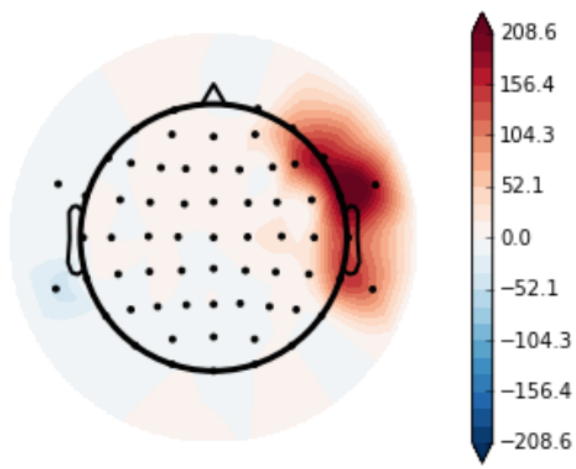
Results

Overview

As noted above, this study addressed three hypotheses.

1. Participants will have a stronger EEG-based anxiety response to cued mathematical questions relative to non-cued mathematical questions.
2. Participants will have a stronger EEG-based anxiety response to feedback about their ability given after the completion of mathematical questions relative to not receiving performance feedback.
3. This EEG-based anxiety response is specific to mathematics and not generalized to overall learning.

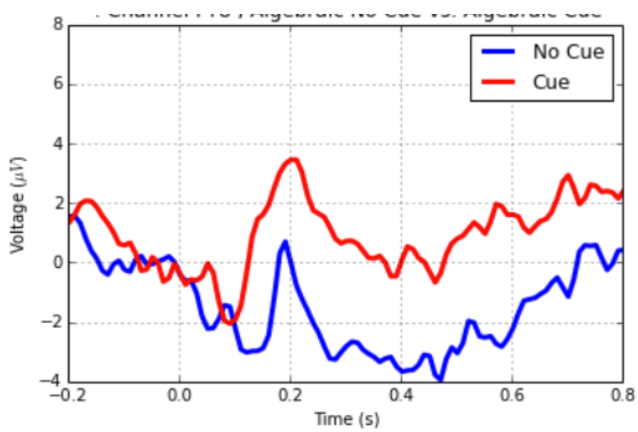
Figure 2: ERSP across all participants during the Arithmetic task – Cue vs. No Cue



Hypothesis 1: Cue vs. No Cue Blocks

With respect to the arithmetic task, the cued condition trended towards a marginally significant positive difference in electrical activity, p = 0.11, within the right anterior frontal region (strongest at electrode T8) at 0.2 s after the stimulus onset (i.e., after the math problem was presented) (See Figures 2 and 3). P-values were calculated by correcting for multiple comparisons between every electrode channel and time point. This means that a t-test was conducted at each time point, which is an extremely large number of comparisons. Therefore,

Figure 3: Electrode channel T8 across all participants during the Arithmetic task – Cue vs. No Cue



this process does not include degrees of freedom or a t-score. Instead, it identifies a threshold at which there is a significant difference between conditions (i.e., p-value).

When examining the algebra task, the cued condition trended towards a positive difference in electrical activity, p = 0.46, within the right parietal region (strongest at electrode P8) between 0.2-0.4 s after the stimulus onset (See Figures 1 and 2 in Appendix A).

Hypothesis 2: Feedback vs. No Feedback Blocks

When investigating the arithmetic task, the feedback condition trended towards a negative difference in electrical activity, p = 0.39, within the dorsal posterior region (strongest at electrode CPz) between 0.2-0.3 s after the stimulus onset (i.e., after the feedback was presented) (See Figures 3 and 4 in Appendix A).

With respect to the algebra task, the feedback condition trended towards a negative difference in electrical activity, p = 0.54, within the left frontal region (strongest at electrode F7) at 0.19 s after the stimulus onset (See Figures 5 and 6 in Appendix A).

Hypothesis 3: Anxiety Response Specific to Mathematics

EEG data collected during the lexical task depicted little to no difference in the cortical electrical activity for both cue vs. no cue blocks, p = 0.23, and feedback vs. no feedback blocks, p = 0.22.

Summary of Results

In review, results suggest participants demonstrate a greater difference in cortical electrical activity in response to the anticipation of an upcoming math problem (i.e., cueing). Additionally, results illustrate that participants also demonstrate a greater difference in cortical electrical activity in response to feedback about their mathematical performance given after the completion of a question. Finally, results depict that the change in cortical functioning was elicited only by mathematical questions and not by lexical problems.

Discussion

The present study utilized an EEG paradigm to examine the following three hypotheses. First, participants would have a stronger EEG-based anxiety response to cued mathematical questions relative to non-cued mathematical questions. Second, participants would have a stronger EEG-based anxiety response to feedback about their ability given after the completion of mathematical questions relative to not receiving performance feedback. Lastly, this EEG-based anxiety response would be elicited only by mathematical questions and not by lexical problems.

With respect to Hypothesis 1, the strongest trend within the data was a marginally significant positive difference in cortical activity between being given a cue before an arithmetic task relative to no cue before an arithmetic task. This study also found a positive difference in cortical activity between being given a cue before an algebraic task relative to no cue before an algebraic task. The findings explained above partially support this study's first hypothesis, which stated participants would have a stronger EEG-based anxiety response to cued mathematical questions relative to non-cued mathematical questions. However, at this time, it is not possible to make strong conclusions given that these findings are not statistically significant.

Moreover, the findings depicted here show a change in cortical functioning, which may or may not be linked to anxiety.

In contrast, when examining Hypothesis 2, results demonstrated a negative difference in cortical activity between being given feedback after both an arithmetic task and an algebraic task relative to no feedback after the tasks. The findings explained above partially support this study's second hypothesis, which stated participants would have a stronger EEG-based anxiety response to feedback about their ability given after the completion of mathematical questions relative to not receiving performance feedback. Again, this difference in the cortical electrical activity is showing a change in cortical functioning, which may or may not be an anxiety response.

When investigating Hypothesis 3, the lexical task findings depicted little to no difference in the cortical electrical activity for both cue vs. no cue blocks and feedback vs. no feedback blocks. The results explained above support this study's third hypothesis, which stated that the difference in the cortical electrical activity is specific to mathematics and not generalized to overall learning.

Moreover, the present data align broadly with pervious results and illustrate that the EEG Anxiety Task discriminates brain function across the lexical, arithmetic, and algebra tasks. As previously piloted on a sample of 15 participants at Tomsk State University, Russia, preliminary results demonstrated that the EEG paradigm distinguishes brain function across the arithmetic, algebra, and lexical tasks across differing levels of mathematical anxiety. As this study continues to collect more participants at OSU, inferential statistics will be applied to these findings, hypothesizing statistically significant differences between cue and feedback for arithmetic and algebra tasks, but not the lexical task. This study will also examine the extent to which these responses vary as a function of overall mathematical, test, and general anxiety.

Additionally, spectral analyses will be conducted once more participants are assessed. In this way, it will be possible to examine specifically for the desynchronization of beta activity, which again has been associated with anxiety in other domains (Pavlenko, Chernyi, & Goubkina, 2010). Future spectral analyses will allow for a deeper investigation into the relationship between mathematical anxiety, desynchronization of beta activity, and working memory processes in real-time (Ashcraft & Krause, 2007; Lyons & Beilock, 2012b).

Limitations and Future Directions

Multiple factors limited this study's results. As mentioned previously, due to this study's low sample size (N = 7) only strong trends were found. Future mathematical anxiety research, utilizing an EEG paradigm, should aim to collect a higher sample size. With a higher power, we hope that the strong trends depicted in the present study may become statistically significant results. Another limitation with this sample is that it consists of university students. This population might not be fully representative of all individuals with mathematical anxiety. Also, this sample was not screened for only high and low math anxious individuals. Lastly, it is important to remember that EEG data reveals only neural correlates, and does not record actual brain activity.

As mentioned previously, in order to delve deeper into understanding the neural correlates of mathematical anxiety, future research utilizing an EEG paradigm should focus on spectral analyses of the data. This will shed more light on the exact brain waves being activated by anticipation before mathematical performance and feedback after mathematical performance. Thus, also allowing for a more comprehensive examination of the anxiety response, working memory, and subsequent performance. Additionally, future research should include measures of mathematical anxiety, general anxiety, and working memory to further examine the relationship between these constructs. This data will aid in understanding both the affective and cognitive physiological consequences associated with math anxiety.

Conclusion

In summary, mathematical anxiety has both affective and cognitive consequences that must be considered when investigating it's neural correlates. Despite this study's limitations, the results depicted above add another critical piece to further understand both the affective and cognitive lens of math anxiety. This study has advanced the knowledge behind mathematical anxiety by also advancing the understanding of temporal processing and going beyond static measures. Given these results, future math anxiety research should attempt to utilize a larger sample size and focus on spectral analyses of EEG data while also including questionnaire-based measures of math anxiety, general anxiety, and test anxiety.

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Appendix A

EEG Anxiety Task Instructions

"This is an error recognition task. In this task, you will be presented with three types of statements. There are sentences, arithmetic equations, and algebraic equations. Here are some examples of the type of statements that you will be presented in the task [*show them on the screen*]. These sentences and equations may or may not contain errors in them. Your job is to decide whether each sentence and equation has errors in it, as accurately and quickly as you can. Are there any questions so far?

We divided this task into 8 sections. Each section will last about 5 minutes. In some sections, you will receive a cue before each statement, telling you whether the upcoming statement is a sentence, an arithmetic equation, or an algebraic equation. An "ABC" means that you will be given a sentence next. A "+/-" means that an arithmetic equation is coming up next. A "square root of X^2" means that an algebraic question is coming up next [*show them on screen while explaining*]. In other sections, you will receive feedback after each statement telling you if you have answered that question correctly or not. A green check mark means you answered that question correctly, and a red X means that you answered incorrectly [*show them on the screen while explaining*]. Still in other sections, you will be presented only with these statements without any cue or feedback. After each section is completed, you will receive an overall feedback concerning how you have performed in that section. Specifically you will be shown the percentage of the lexical, arithmetic, and algebraic questions that you answered correctly. You will also see your average response time for each of these three types of statements, just like this [*shown example on the screen while explaining*]. Are there any questions about these different sections?

To indicate your answer, please put one finger on the "Z" key and another finger on the "/" key. Please use both hands. *Press the Z key if the sentence or equation is correct and press the back slash key if the sentence or equation is incorrect.* <u>(Reminder: odd number participants – Z = correct, / = incorrect; even number participants – Z = incorrect, / = correct)</u>. Before each section, you will be reminded which key maps onto which response.

Now, you will have a chance to practice the task just to get you warm up. Please press the space bar to start the practice [*while they are practicing, get a sense if they are still confused, such as from their facial or verbal expression*].

A couple of notes before you start the real test. These cues and feedbacks you just saw only appear in some sections and not others. There will be sound coming out of this speaker right here sporadically throughout the task. These sounds are randomly produced, and are not associated with your performance at all. So please do not spend efforts on trying to figure out a pattern here, because there is none. We also ask you to find a comfortable position and try to stay as still as possible during the task, because too much movement may bring artifact that will affect the results of the study. We realize that this can be hard. You can, of course, still blink and move a little, just try not to constantly move your head around or jiggle your legs, etc [*check if they are chewing gum*]. In addition, you can also take a break, such as stretch your leg after you've finished one section and before you start the next section. We purposefully break down the task into sections so you have a chance to take a break. If you have any question or need us for anything, please just wave at this camera, and we can see you from the outside. OK? Any questions? Alright! Press the space bar to begin the real test whenever you are ready!"

<u>ABOUT ME</u>

Age: ______ years _______months

Years of education completed (e.g. current college freshman is 12): _______

Sex (circle one): Male Female

Is English your native language?: Yes No, my native language is ________________________

Ethnicity (check one):
□ Hispanic or Latino
□ Not Hispanic or Latino

Race (check all that apply):
□ American Indian/Alaska Native
□ Asian
□ Native Hawaiian or Other Pacific Islander
□ Black or African American
□ White

Standardized Test Scores and Course Work:
Please complete the following items to the best of your knowledge. If something does not apply, please write "NA". If you do not remember, please write "DK".

1. SAT COMBINED SCORE:______________________

2. SAT MATH SCORE:___________________________

3. SAT VERBAL SCORE:__________________________

4. ACT COMPOSITE SCORE:_____________________

5. ACT ENGLISH SCORE:________________________

6. ACT MATH SCORE:___________________________

7. ACT READING SCORE:________________________

8. ACT SCIENCE SCORE:_________________________

High school GPA _________________ out of (total; e.g., 4.0) ______________________

College GPA ____________________ out of (total) ________________________

College GPA in major ________________ out of (total) _______________________

Major (or intended major): ____

State-Trait Anxiety Inventory

SELF-EVALUATION QUESTIONNAIRE

DIRECTIONS

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you *generally* feel.

	ALMOST NEVER	SOMETIMES	OFTEN	ALMOST ALWAYS
21. I feel pleasant	1	2	3	4
22. I feel nervous and restless	1	2	3	4
23. I feel satisfied with myself	1	2	3	4
24. I wish I could be as happy as others seem to be	1	2	3	4
25. I feel like a failure	1	2	3	4
26. I feel rested	1	2	3	4
27. I am "calm, cool, and collected"	1	2	3	4
28. I feel that difficulties are piling up so that I cannot overcome them	1	2	3	4
29. I worry too much over something that really doesn't matter	1	2	3	4
30. I am happy	1	2	3	4
31. I have disturbing thoughts	1	2	3	4
32. I lack self-confidence	1	2	3	4
33. I feel secure	1	2	3	4
34. I make decisions easily	1	2	3	4
35. I feel inadequate	1	2	3	4
36. I am content	1	2	3	4
37. Some unimportant thought runs through my mind and bothers me	1	2	3	4
38. I take disappointments so keenly that I can't put them out of my mind	1	2	3	4
39. I am a steady person	1	2	3	4
40. I get in a state of tension or turmoil as I think over my recent concerns and interests	1	2	3	4

Mathematics Anxiety Rating Scale (MARS)

Self-Evaluation Questionnaire II

FOR EACH OF THE FOLLOWING ITEMS, INDICATE HOW MUCH THE SITUATIONFRIGHTENS YOU.

Use a five-point scale ranging from 1 (not at all) to 5 (very much).

	not at all				**very much**
1. Buying a mathematics textbook	1	2	3	4	5
2. Watching a teacher work on an algebraic equation on the blackboard	1	2	3	4	5
3. Signing up for a math course	1	2	3	4	5
4. Listening to another student explain a math formula	1	2	3	4	5
5. Walking into a math class	1	2	3	4	5
6. Studying for a math test	1	2	3	4	5
7. Taking math section of college entrance exam	1	2	3	4	5
8. Reading a cash register receipt after your purchase	1	2	3	4	5
9. Taking an exam (quiz) in a math course	1	2	3	4	5
10. Taking an exam (final) in a math course	1	2	3	4	5
11. Being given a set of numerical problems involving addition to solve on paper	1	2	3	4	5
12. Being given a set of subtraction problems to solve	1	2	3	4	5
13. Being given a set of multiplication problems to solve	1	2	3	4	5
14. Being given a set of division problems to solve	1	2	3	4	5
15. Picking up math textbook to begin working on a homework assignment	1	2	3	4	5

	not at all				very much
16. Being given homework assignments of many difficult problems that are due the next class meeting	1	2	3	4	5
17. Thinking about an upcoming math test 1 week before	1	2	3	4	5
18. Thinking about an upcoming math test 1 day before	1	2	3	4	5
19. Thinking about an upcoming math test 1 hour before	1	2	3	4	5
20. Realizing you have to take a certain number of math classes to fulfill requirements	1	2	3	4	5
21. Picking up math textbook to begin a difficult reading assignment	1	2	3	4	5
22. Receiving your final math grade in the mail	1	2	3	4	5
23. Opening a math or stat book and seeing a page full of problems	1	2	3	4	5
24. Getting ready to study for a math test	1	2	3	4	5
25. Being given a "pop" quiz in a math class	1	2	3	4	5

Figure 1: ERSP across all participants during the Algebra task – Cue vs. No Cue

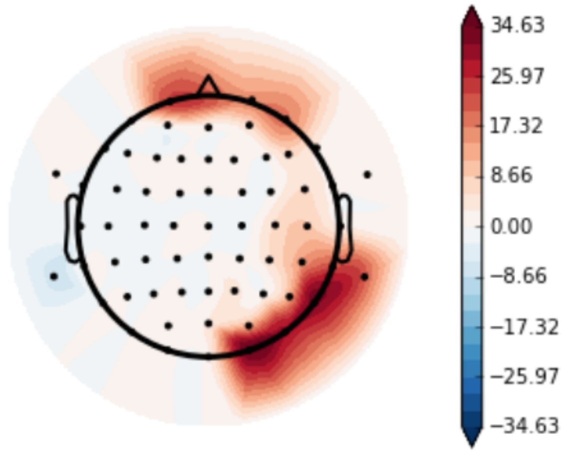

Figure 2: Electrode channel P8 across all participants during the Algebra task – Cue vs. No Cue

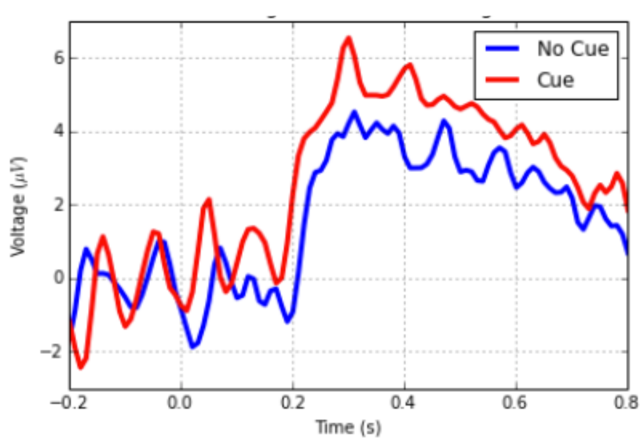

Figure 3: ERSP across all participants during the Arithmetic task – Feedback vs. No Feedback

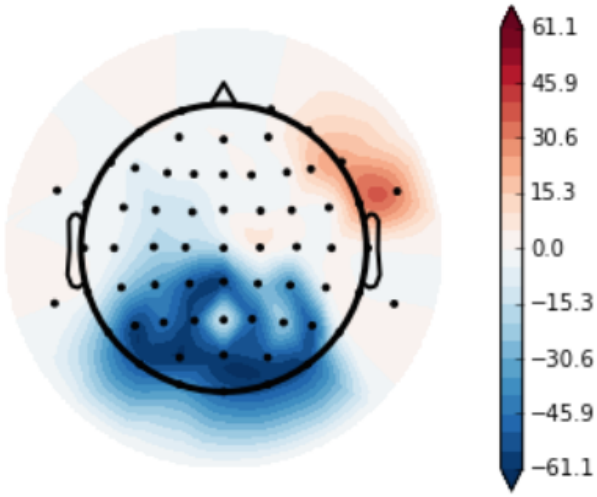

Figure 4: Electrode channel CPz across all participants during the Arithmetic task – Feedback vs. No Feedback

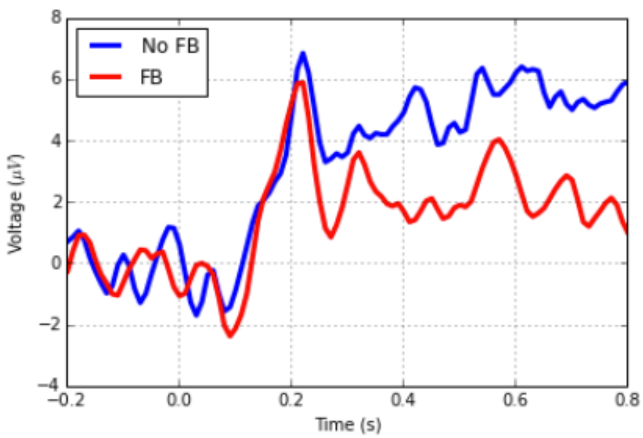

Figure 5: ERSP across all participants during the Algebra task – Feedback vs. No Feedback

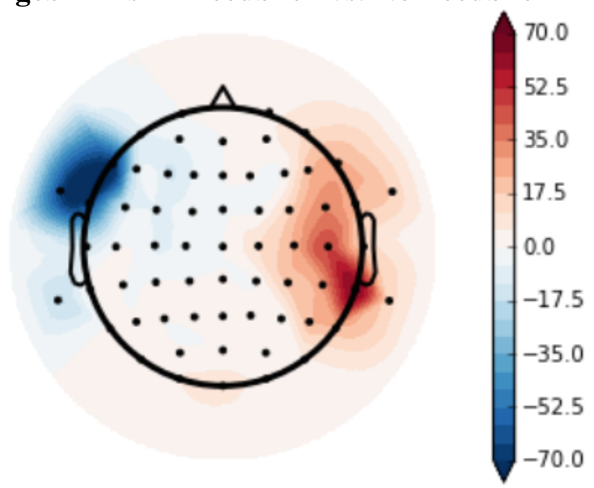

Figure 6: Electrode channel F7 across all participants during the Algebra task – Feedback vs. No Feedback